Ozark UNDERGROUND LABORATORY 1572 Aley Lane • Protem, MO 65733 • (417) 785-4289 • fax (417) 785-4290 • contact@ozarkundergroundlab.com

October 11, 2012

Jean A. Mescher
McKesson Corporation
One Post Street, 34th Floor
San Francisco, CA 94104

Re: Arkwood, Inc. Superfund Site

Dear Ms. Mescher:

I have reviewed the Arkwood, Inc. Superfund Site Groundwater Remediation Summary dated June 2012 (Revised August 2012) and the August 9 2012 letter from you to Mr. Stephen Tzhone of EPA. I have also reviewed a substantial amount of existing site information including the 1992 "Groundwater Tracing Investigation" (Aley 1992) that I conducted at and around the site. Based on this information and comments raised by EPA, I have identified three issues I wish to address. They are:

1. The possibility that the 1991-1992 groundwater tracing study did not adequately identify all flow paths for contaminants derived from the Arkwood site.
2. The nature of the groundwater flow system existing between the former sinkhole area and New Cricket Spring, and the likelihood that intermediate monitoring wells could intercept such flow and yield useful data.
3. The appropriateness of the enhanced ozone treatment strategy for this hydrogeologic setting.

A copy of my resume is attached in Appendix B. I am nationally certified as a hydrogeologist by the American Institute of Hydrology and have extensive experience in the hydrology of karst areas in the Ozarks and elsewhere. I am licensed as a Professional Geologist in Arkansas, Missouri, Kentucky, and Alabama. I have taught at least 20 professional short-courses with titles such as "Practical Karst Hydrogeology with Emphasis on Groundwater Monitoring", and have taught these for various professional organizations including the Association of Ground Water Scientists and Engineers (a professional division of the National Water Well Association). Finally, I am very familiar with the Arkwood site and with the hydrogeology of the geologic units present.

Issue 1. The possibility that the 1991-1992 groundwater tracing study did not adequately identify all flow paths for contaminants derived from the Arkwood site.

There were two different dye introduction points for the groundwater tracing study. They were located 3,100 feet apart and bracketed the Arkwood site. The dye introduction points were designed to identify all points to which contaminated water from the Arkwood site would flow.

There were a total of 79 sampling stations used during this groundwater tracing study. Four of these were wells and 28 were springs. Four of the springs were in the railroad tunnel that is adjacent to and at an elevation lower than most of the Arkwood site. The sampling locations surrounded the Arkwood site.

Trace 91-01 was the Woodchip Pile Trace. This was the dye introduction point on the southeast end of the Arkwood site. The dye introduction point was within the Cricket Creek [J1]topographic basin. Dye introduced at this point was detected at a total of 12 sampling stations. These included all of the springs within the railroad tunnel (including water discharging from both ends of the tunnel) and in stream flow and springs easterly and downstream of the tunnel in Walnut Creek and in Barren Fork Creek downstream of the point where that stream receives water from Walnut Creek. All of these sampling stations were in the Walnut Creek topographic basin or received water from this basin.

Trace 91-02 was the New Cricket Spring Trace. This was the dye introduction point on the northwestern end of the Arkwood site. Dye introduced at this point was detected at a total of 14 sampling stations, all of which were in the Cricket Creek topographic basin. The dye introduction point was within the Cricket Creek topographic basin.

Both Cricket Creek and Walnut Creek are gaining (rather than losing) streams once one gets a very short distance downstream of the Arkwood site. This greatly minimizes the possibility that water derived from the Arkwood site would move into groundwater supplies outside of these two topographic basins.

Given the above conditions it is my conclusion that the dye tracing study identified all potential receptor sites for contaminants yielded from the Arkwood site[J2].

Issue 2. The nature of the groundwater flow system existing between the former sinkhole area and New Cricket Spring, and the likelihood that intermediate monitoring wells could intercept such flow and yield useful data.

The Arkwood site is underlain by the Boone Formation and the St. Joe Formation (ERM 1989). The area in the immediate vicinity of where most of the wood treating was conducted is mapped as Boone Formation, and New Cricket Spring discharges from the St. Joe Formation. The St. Joe Formation in Arkansas has often been considered to be a unit of the Boone Formation. Both formations are predominantly limestone with chert being less abundant in the St. Joe Formation.

An epikarstic zone is routinely found in the upper 15 to 20 feet of the Boone and St. Joe Formations. The epikarstic zone exists immediately below the overlying residuum. All soil was removed from the Arkwood site to allow for use of the site for wood treating. The epikarstic zone consists of a very irregular bedrock surface with numerous solutional openings in the rock, many of which are partially to almost completely filled with fine sediments.

Both the Boone and St. Joe Formations are cavernous karst units where groundwater flow is along solutionally-widened joints and bedding planes. Groundwater flow along fractures that have not been solutionally enlarged is negligible, so this should be viewed as a karst aquifer rather than as a fractured rock aquifer. Karst aquifers have been solutionally modified by the passing water to create a hydrologically integrated flow system to transport groundwater in a down-gradient direction. In contrast, fractured rock aquifers have not been modified by the passing water and do not provide this integrated flow system.

The extent of water transport through this epikarstic aquifer to New Cricket Spring is well demonstrated by the flow rate data from this spring provided in the "Arkwood, Inc. Superfund Site Groundwater Remediation Summary June 2012 (Revised August 2012)". Those data show the following:

- There are 229 flow rate measurements made between July 2, 1996 and May 23, 2012.
- Flow rates range from 0.132 gallons per minute (gpm) to 636 gpm. The peak observed flow is 3.5 orders of magnitude greater than the minimum observed flow. Such a wide range in flow rates is typical of small and well integrated eipkarstic aquifers.
- 86% of the flow rate measurements are less than 10% of the peak observed flow rate. This also demonstrates a well-integrated karst aquifer.
- Flow rates recede rapidly after a peak flow event; this is shown by the following flow rates in 2006.
    - 11/30 flow 636 gpm
    - 12/4 flow 59 gpm
    - 12/6 flow 37 gpm
    - 12/18 flow 21 gpm

Attached as Appendix A is a short publication on groundwater tracing in the epikarst (Aley 1997) that will hopefully be helpful to the reader. It groups epikarstic zones into (1) rapidly draining, (2) seasonally saturated, and (3) perennially saturated zones. Based upon my experience and the flow data from New Cricket Spring, the Arkwood site is underlain by a rapidly draining epikarstic zone.

A sinkhole existed adjacent to the area used for treating wood with creosote and pentachlorophenol (PCP). The sinkhole was capped with concrete during remediation work. This sinkhole existed because water had dissolved the soluble bedrock and developed an integrated system of natural conduits that conveyed water to New Cricket Spring, a straight-line distance of about 1,200 feet. Sinkholes such as this also convey sediment and other materials into the karst aquifer and toward receiving springs. In the case of this sinkhole the materials introduced into it included sediment, sawdust, wood waste, and contaminants including PCP.

The sinkhole functioned as a major introduction point for PCP into the epikarstic zone. While dye has never been introduced into the sinkhole or any of the wells into which ozone was injected, in my experience such dye introductions would likely first reach New Cricket Spring within a day or less. The residual PCP that has been treated during remediation efforts was detained within the epikarstic zone and is slowly discharging from cavities and especially from sediments within the epikarstic zone.

Given the nature of the karst aquifer, monitoring New Cricket Spring for PCP provides far more useful and credible data than would be obtained from monitoring wells located between the capped sinkhole and the spring. The aquifer is highly heterogeneous and anisotropic and there is no reason to believe that any well or group of wells would yield representative data. In contrast, the spring provides a point that realistically samples for contaminants discharging from groundwater beneath the site. The spring also provides a very fortuitous location for capture and treatment of contaminated waters derived from the site.

Issue 3. The appropriateness of the enhanced ozone treatment strategy for this hydrogeologic setting.

The enhanced ozone treatment was used in addition to the planned treatment at New Cricket Spring. The rationale for the treatment was three-fold. First, that make-up water was often needed for proper operation of the treatment equipment at New Cricket Spring. Second, that adding the make-up water to the contaminated karst aquifer could help flush contaminated water to the spring where it could be treated and would thus speed up site remediation. Third, that introducing ozonated water into the aquifer near the source of contamination would provide some in-situ treatment and thus enhance site remediation.

The enhanced ozone treatment approach was as follows:

- Groundwater was extracted from a deep aquifer that was not impacted from any of the past or present activities at the Arkwood site. The contaminated shallow epikarstic aquifer was incapable of producing a dependable yield of 20 gallons per minute, and this was the volume needed to ensure desirable operating conditions for treatment at New Cricket Spring.
- Using an ozone generation system, ozone was dissolved in the water and then conveyed to shallow injection wells that injected the ozonated water into the epikarstic aquifer. A total of nine injection wells with depths of 16 feet or less were constructed, but only five of them proved capable of injecting water at a rate of up to 35 gpm. The wells were located in an area a short distance west of the capped sinkhole.
- Wells used for injecting the ozonated water were wells A, B, C, D, and I. From 2007 to 2009, they were used on a rotating basis.

The EPA comment letter expressed concern that the ozone treatment would treat only a small area. That would be true if this were, for example, an alluvial or sandstone aquifer. It is not. It is a karst aquifer where groundwater movement is preferentially along solutionally-dissolved conduits, and where travel rates are often on the order of tens to hundreds of feet per hour. In a few cases, ozone treated water was detected at New Cricket Spring, about 1,200 feet from the injection site. As a result, the enhanced ozone treatment strategy for this site was both reasonable and prudent. It represented an excellent adaptation to the hydrogeologic conditions existing at the site.

Summary

In June 1990, EPA issued a "Proposed Plan of Action" for the Arkwood Site. On pages 8 and 9 are the following statements:

"Because of the high degree of uncertainty in aquifer flow in a karst terrain, routine methods for determining where contamination is spreading, such as ground water monitor wells and modeling are of little practical use at the Arkwood site. The geology of the area also prevents the use of traditional ground water remediation techniques such as pumping and treating. For these reasons a dye tracing study has been initiated in the site area. A dye tracing study will determine as accurately as possible where the ground water goes after it leaves the site. This study should be completed this summer, with the results available several months later. The results will be used to evaluate the remedial alternative for the groundwater, and will be used in the design phase of the remediation to ensure public health is protected. While the results of this study will not be available before a decision is made on this Proposed Plan of Action, the study results will be used to assess any additional action on the groundwater that may be necessary."

In September 1990, EPA issued a "Superfund Record of Decision" for the Arkwood Site. On page 2 are the following statements:

"Shallow ground water on the site is contaminated with PCP. Only one spring in the area, New Cricket Spring, which lies approximately 1,000 feet northwest of the site, has consistently shown contamination with PCP. No drinking water wells have been shown [to be affected by] the presence of site contaminants. The area is underlain by karst geology which prevents the use of monitor wells as a method of predicting contaminant movement, or recovery wells as a method of remediation. Therefore, ground water remediation focuses on New Cricket Spring."

In this letter I have addressed three issues raised by the recent EPA comments. My comments demonstrate that, since a karst aquifer underlies the site, investigations and strategies relevant to a karst aquifer were appropriate for the site and were appropriately implemented. Work for the past 22 years at this site has been based upon this hydrogeologic recognition and there are no data to suggest that any different strategies should now be considered.

Sincerely,

Thomas Aley

Thomas Aley, PHG 179* and Arkansas PG 1646
President and Senior Hydrogeologist
Ozark Underground Laboratory, Inc.

* Professional Hydrogeologist #179, certified by American Institute of Hydrology.

References

Aley, Thomas. 1992. Final report: Groundwater tracing investigation Arkwood, Inc. site, Omaha, Arkansas. Volumes 1 and 2. Ozark Underground Laboratory contract report to ERM-Southwest, Inc. 84p. + appendixes and analytical graphs.

Aley, Thomas. 1997. Groundwater tracing in the epikarst. IN: *The Engineering Geology and Hydrogeology of Karst Terranes; Proc. 6th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst.* A.A. Balkema, Rotterdam, pp. 207-211.

ERM-Southwest, Inc. 1990. Remedial investigation report Arkwood, Inc. Site. Vol. 1. ERM-Southwest contract report for Mass Merchandisers, Inc. 350p. approx.

APPENDIX A

"Groundwater Tracing in the Epikarst"

The Engineering Geology and Hydrogeology of Karst Terranes, Beck & Stephenson (eds)
© 1997 Balkema, Rotterdam. ISBN 90 5410 867 3

Groundwater tracing in the epikarst

THOMAS ALEY Ozark Underground Laboratory, Protem, Mo., USA

ABSTRACT

The epikarst is the dissolutionally weathered upper portion of the bedrock in carbonate landscapes. Its thickness is commonly on the order of 10 meters (33 feet), but may be appreciably thicker or thinner. At many waste sites in karst settings the majority of the contaminants are localized and detained within the epikarst.

Epikarstic Dye Introduction Points (EDIPs) provide a cost effective and hydrologically appropriate method for introducing tracer dyes into the epikarst. Tracer dyes introduced into EDIPs are routinely recovered at monitoring wells and springs at sites where the water table is within the epikarstic zone. Dye tracing tests in the epikarst have often failed due to the use of inappropriate dyes, an insufficient quantity of dye and/or water, and the absence of a good study design utilizing quantitative dye analysis methods. Dye tracing in the epikarst is routinely essential and can be effectively conducted.

INTRODUCTION

The epikarstic zone is the dissolutionally weathered upper portion of the bedrock in carbonate landscapes; it has sometimes been called the subcutaneous layer. At many waste sites in karst settings the majority of the potential contaminants of concern are localized and detained within the epikarstic zone. As a result, appropriate site characterization must focus on the epikarstic zone and its hydrologic functioning.

Groundwater tracing with fluorescent dyes should be a routine component of site characterization work at karst sites. However, effective tracing in epikarstic zones is typically more complex than most of the groundwater tracing work reported upon in the scientific literature. As contrasted with the commonly published karst groundwater tracing reports, tracing in the epikarstic zone (especially in industrial settings) typically requires: (1) more detailed and quantitative characterization of background fluorescence characteristics, (2) more careful selection of dye types, (3) simultaneous use of multiple dyes with dye quantities and analytical approaches selected to minimize the chance that small dye recoveries of one dye are obscured by another dye, (4) much more extensive sampling and quantitative analysis, and (5) dye introductions at points other than sinkholes and losing streams.

This paper is designed for practicing professionals, and will hopefully be particularly useful for those considering having a groundwater tracing study of an epikarstic zone conducted. Classifications and generalities are designed for practical utility. The comments and conclusions in this paper are based upon the results of about 30,000 quantitative dye analysis samples (including both water and activated carbon samples) and about 1,000 positive groundwater traces. All of these traces have been partially to dominantly focused on characterizing flow through epikarstic zones, and all data are from tracing work conducted by the Ozark Underground Laboratory. Much of the individual site information is client confidential; for this and other reasons we have not identified any specific sites. The majority of the work has been conducted in temperate regions of the central and eastern United States, and most of the associated bedrock units have been Paleozoic limestones and dolomites. Bedding has ranged from nearly flat to nearly vertical; structural features at the sites have also varied dramatically.

SOME PHYSICAL CHARACTERISTICS OF THE EPIKARSTIC ZONE

The thickness of the epikarstic zone is commonly on the order of 10 meters, but can vary from essentially zero to 30 meters (100 feet) or more. Factors effecting the thickness of the epikarstic zone include climate, time since the last glaciation of the site, patterns and depth of groundwater circulation, characteristics of the bedrock, and the vegetational history of the area.

The intensity of epikarstic development, which can be expressed as a percent of the bedrock which has been removed by dissolution, is highly variable. It can vary from less than 1% to more than 50%. The percentage routinely decreases with increasing depth below the surface. In many epikarstic zones sediments partially or almost completely fill most or almost all of the voids within the bedrock; in other situations many or most of the voids are largely free of sediments. The percent of the bedrock void volume which is filled with sediment can range from less than 5% to more than 95%.

Permeability rates within the sediment fillings of the epikarstic zone are also highly variable. The permeability rates of the sediment fillings are often greater than might be anticipated from soils having similar textural characteristics. This is especially true when the fills are silts and silty clays that have been subjected at some time in the past (perhaps only during the 100 year or longer interval droughts) to some desiccation. Periods of desiccation commonly result in compaction of silts and silty clay sediments with associated development of compaction cracks within the sediments filling the voids. These compaction cracks, and other structural and textural features within the sediment fills, often provide matrixes with high permeability rates. The net result is that permeability rates through the sediment fills of the epikarstic zone are commonly orders of magnitude larger than those in the adjacent carbonate bedrock.

HYDROLOGICAL CLASSES OF EPIKARSTS

We have divided epikarstic zones into three hydrological types based upon their ability to store water; they are: (1) rapid draining epikarsts, (2) seasonally saturated epikarsts, and (3) perennially saturated epikarsts. This classification is useful in planning and designing groundwater tracing studies and is developed for this purpose. The quantities of tracer dyes needed and typical groundwater travel rates vary with the type of epikarstic system.

Especially in some thick epikarstic zones, but to some extent in all epikarstic zones, conditions typical of two or more of the hydrological classes of epikarsts may be present. As an example, a rapid draining epikarst may occur in the upper part of the zone while conditions typical of seasonally saturated epikarst or perennially saturated epikarst are found the lower part of the zone.

Rapid draining epikarsts are characterized by having little if any of the epikarstic zone saturated with water for more than a few hours at a time even following major storm events or snow melt periods. In these cases there is little water storage or detainment within the epikarstic zone. Dissolutional voids are typically relatively free of fine textured sediments. However, as is the case with all epikarstic zone drainage, waters entering the subsurface at a particular point may subsequently discharge from multiple points in multiple areas. Areas commonly characterized by rapid draining epikarst include: (1) many alpine karst areas, (2) areas with high topographic relief, and (3) areas where the soluble purity of the carbonate bedrock is high and external sediment sources are negligible; these conditions typically result in thin soils and minimal residuum.

Seasonally saturated epikarsts routinely store water seasonally or after major precipitation periods. This water storage may persist for periods of weeks or months. Dissolutional voids are commonly partially to almost completely filled with fine textured sediment; some preferential flow routes which contain appreciable air-filled void space typically exist. Lands commonly characterized by seasonally saturated epikarst include: (1) humid lands, (2) areas with moderate relief, (3) areas where the soluble purity of the carbonate bedrock has permitted the development of appreciable soil and residuum thicknesses, and (4) areas where most or all of the epikarstic zone is at elevations greater than the elevations of nearby perennial streams.

Perennially saturated epikarsts are characterized by most of the epikarstic zone being perennially saturated with water. This situation is common in: 1) humid lands, (2) areas with low to moderate relief, and (3) areas along perennial streams. Cavities within the bedrock are commonly mostly filled with fine textured sediments.

DESIGNING GROUNDWATER TRACING STUDIES IN EPIKARSTIC ZONES

General Applicability of the Literature

Most karst groundwater tracing reported in the technical literature has utilized dye introduction points that poorly characterize the functioning of the epikarstic zone. Dye introduction into a cave stream is a good illustration; except in rare situations, such a dye introduction yields little information about the hydrologic functioning of the epikarst. Sinkholes have been used as dye introduction points for hundreds of groundwater traces. If the sinkhole provides a direct and open connection to a major groundwater transport conduit (such as a cave stream), the sinkhole dye introduction provides little information about the functioning of the epikarstic zone. However, not all sinkholes provide direct and open connections to major groundwater transport conduits; some sinkholes are discrete water input points into the epikarstic zone and as such may be appropriate dye introduction points for characterizing flow through the epikarstic zone. In many cases it is difficult to determine from a surficial examination whether or not a particular sinkhole yields water to the epikarstic zone.

Losing (or sinking) streams have also been common sites for tracer dye introduction. As is the case with sinkholes, some of the sinking points provide direct and open connections to major groundwater transport conduits. These are often located at or near the downstream terminus of perennial or seasonal water flow in the surface stream. Other losing stream segments (and particularly those on very small surface water courses which have only occasional flow) recharge the epikarstic zone.

In addition, most groundwater tracing reported in the literature for karst areas has been conducted in areas relatively near springs. Such areas are typically remote from recharge area boundaries or areas that contribute to more than one spring. The extent of epikarstic development in the areas more remote from springs may be greater than, or at least different from, conditions in areas nearer the springs. Groundwater travel rates may often be lower in areas more remote from the springs than in the near-spring areas.

In summary, the groundwater tracing results and recommendations reported in the karst hydrology literature are skewed in favor of simple groundwater traces that typically are not reflective of groundwater flow conditions in epikarstic zones. It is relatively easy to conduct dye traces from points where surface water is naturally available, or from points where it can be introduced without any construction work; such sites often inadequately reflect typical conditions operating in regional epikarstic zones. Construction and hydrologic testing of points for introducing tracer dyes into the epikarst is more expensive and requires substantial expertise; as a result, this approach is not routinely used for the studies reported upon in the published literature. Additionally, it is relatively easy to do groundwater tracing near the likely discharging springs since only a few sampling stations are needed and the sampling can be completed in a few days or weeks; results from such studies dominate the technical literature. Finally, the tracing results reported in the published literature are skewed in favor of groundwater traces where relatively unsophisticated sampling and analysis approaches were adequate; such approaches are seldom adequate for detailed epikarstic zone characterization.

It is not our intent to diminish the importance of the groundwater tracing which has been reported in the technical literature. However, the existing literature could lead one to a set of general conclusions (three of which we will discuss) which are not reflective of conditions typically encountered in tracing work in seasonally or perennially saturated epikarstic zones.

First, the existing literature could lead one to conclude that 20 to 50% of the introduced dyes should be expected to discharge from dye recovery sites, and that a number of different dyes can be successfully used. Based upon our experience in epikarstic tracing work, dye recovery rates are commonly 0.1% to 1% for the permanently saturated epikarstic zones, and from 1% to 10% for the seasonally saturated zones.

Second, dye recovery percentages calculated above are related only to the most mobile dyes; some dyes are unsuited for use in some epikarstic zones. The most mobile and stable dyes for tracing in epikarstic zones are fluorescein (Acid Yellow 73) and eosine (Acid Red 87). Dyes such as rhodamine WT (Acid Red 388) and sulforhodamine B (Acid Red 52) can be totally lost during tracing in epikarstic zones, especially in perennially saturated epikarsts. Other dyes such as the optical brighteners and Direct Yellow 96 are seldom suitable for tracing in seasonally or perennially saturated epikarst.

Third, the existing literature might lead one to conclude that groundwater travel rates in karst settings are routinely hundreds to thousands of meters (or for that matter, feet) per day. While this can be the case in rapid draining epikarst, much slower travel rates must be anticipated in seasonally or perennially saturated epikarstic zones, especially when the rates of concern are reflective of travel to monitoring or slow-rate pumping wells rather than to springs.

In a perennially saturated epikarstic zone tracing study dyes were recovered from 20 monitoring wells. The mean travel rate for first arrival of tracer dyes at the wells was 6.7 meters (22 feet) per day; the values ranged from 15 cm (0.5 feet) per day to 25.6 meters (84 feet) per day. The mean travel rate for the peak dye concentrations at these wells was 4.3 meters (14 feet) per day; the values ranged from 0.25 cm (0.1 feet) to 25.6 meters (84 feet) per day. The mean travel distance for wells with first dye arrival travel rates of less than 6.7 (22 feet) per day was 60.7 meters (199 feet); the mean travel distance for wells with first dye arrival travel rates greater than 6.7 meters (22 feet) per day was 213 meters (700 feet). This indicates that, in general, the greater the travel distance the more rapid the mean travel rate.

In a series of 50 traces in seasonally saturated epikarstic zones, the mean first arrival travel rate to monitoring wells was 60 meters (197 feet) per day. This is about an order of magnitude more rapid than those encountered in the perennially saturated epikarstic zone study. The mean peak dye arrival travel rate was 22.6 meters (74 feet) per day in this seasonally saturated epikarstic zone.

In summary, we urge readers concerned with groundwater movement through the epikarstic zone to view the technical karst hydrology literature with caution. If you are involved with seasonally or perennial saturated epikarstic zones, dye recoveries may be one or two orders of magnitude lower than the technical literature might suggest. Travel rates may be one or two orders of magnitude slower than the literature might suggest. Finally, some of the tracer dyes may be inappropriate for tracing in the epikarstic zone or else may have significant limitations.

Introducing Dyes into the Epikarstic Zone

Groundwater tracing is often needed to determine the point or points to which water moves from a particular point or particular small area. Introducing a tracer dye into a sinkhole or losing stream segment a hundred meters (300 feet) or more away from the point or area of concern may be irrelevant for answering the questions that need to be addressed. How, then, do we introduce tracer dyes to clearly address site-specific issues?

In some cases one can introduce tracer dyes in drainage ditches around features such as closed lagoons to address issues such as the points to which groundwaters move from the lagoon area. Multiple dyes can often be used to bracket such features. One of several disadvantages to this approach is that subsequent storms may flush residual tracer dyes downstream in the ditches and yield dye recoveries at points which do not receive groundwater from the area where the dye was initially placed.

If the top of the epikarstic zone is relatively near the surface a dye introduction trench can be constructed with a back-hoe and used for introducing a tracer dye. Typical trenches are on the order of 5 meters (16.4 feet) to 10 meters (32.8 feet) long, and are tested prior to dye introduction to insure that they recharge groundwater. A common specification is that an acceptable trench for dye introduction must lose a minimum of 1900 liters (500 gallons) of water to the subsurface at a rate of at least 6 liters (1.5 gallons) per minute (and preferably more). Additional trenches are constructed and tested until an adequate number of acceptable dye introduction trenches in appropriate areas have been constructed. Dyes and water are then introduced into the trenches and allowed to drain until there is little or no pooled water remaining in the trench. The trench is then back-filled with the soil that was previously excavated.

Dye introduction trenches which do not bottom in the epikarstic zone can be used in deeper soils and residuum if the infiltration rate is sufficiently great. Preferential flow routes (macropores) through soil and residuum are common in karst areas, and are an important part of the explanation for the rapid response to precipitation which characterizes many monitoring wells developed within epikarstic zones. Laboratory permeability rates for the associated soils and residuum are of little utility in assessing the extent of macropore permeability. In many cases the most practical approach is to dig a trench or two, add about 1,900 liters (500 gallons) of water to each, and measure the rate of water loss. We have successfully used dye introduction trenches for a number of groundwater traces; these have included trenches which bottomed in the epikarstic zone and trenches which did not. Silty clay and clay soil and residuum thicknesses beneath successful dye introduction trenches have been as great as 18 meters (60 feet).

Dye introduction trenches which do not bottom in the epikarstic zone are likely to require the use of more dye than would be the case if the water and dye are introduced directly into the epikarstic zone. As a rule of thumb, dye introductions into trenches that do not bottom in the epikarstic zone require two to ten times more dye than would be required if dye introduction is directly into the epikarstic zone. Furthermore, some tracer dyes are subject to appreciable adsorption onto soil particles, and thus are poorly suited for use in dye introduction trenches.

We commonly construct Epikarstic Dye Introduction Points (EDIPs) when doing groundwater tracing studies at waste sites. EDIPs are constructed in a fashion similar to monitoring wells. They extend through the soil and residuum and about 1.5 meters (5 feet) into the bedrock. The reason for entering the bedrock is that the weathered top of the bedrock is often soft and tends to plug small openings. About 2 meters (6.5 feet) of pea gravel is placed in the bottom of the EDIP, and a 10 cm (4 inch) to 15 cm (6 inch) diameter casing is set and grouted in place with bentonite on top of the gravel. After completion, EDIPs are tested to insure that they will accept water at a reasonable rate. We commonly specify that they accept a total of 1,900 liters (500 gallons) of water at a rate of at least 19 liters (5 gallons) per minute. If this rate is not obtained, a second EDIP is constructed nearby and tested. If neither EDIP accepts 1,900 liters (500 gallons) of water at a rate of at least 19 liters (5 gallons) per minute, then the EDIP which has the higher rate of water acceptance is used if the rate is at least 7.5 liters (2 gallons) per minute. Our experience has been that about 75% of the EDIPs constructed meet the water acceptance criteria.

EDIPs are superior to most monitoring wells for dye introduction since they are specifically designed to introduce dye and water at the top of the epikarstic zone. This is the area that typically has the greatest lateral permeability. In contrast, while some monitoring wells may be screened into this zone, it has been our experience that most monitoring wells at waste sites have excluded the uppermost portion of the epikarst. In most cases we bracket a localized area of concern with two (or rarely three) EDIPs; the same type of tracer dye is introduced into each of the bracketing EDIPs.

Dye introductions into EDIPs are typically preceded by 380 liters (100 gallons) to 760 liters (200 gallons) of water and are followed with 5,700 liters (1,500 gallons) to 9,500 liters (2,500 gallons) of water introduced at a rate lower than the EDIP's ability to accept the water. This can be done from hydrants or portable tanks; the ability to control the flow rate is crucial.

Selection of Tracer Dyes

Fluorescein and eosine are generally the most appropriate tracer dyes for use in epikarstic zones; fluorescein is by far the better of the two. Rhodamine WT can commonly be used, but it is may suffer excessive adsorptive losses and biological decomposition. In some cases pyranine (D&C Green 8) can be used, but its use will necessitate appreciable analytical work. Sulforhodamine B has some limited utility. Other tracer dyes (and particularly those adsorbed onto cotton samplers) generally have limited utility in seasonally or perennially saturated epikarstic zones.

Sampling and Dye Analysis Strategy

Most groundwater tracing in epikarstic zones will include appreciable sampling for the dyes in non-pumping wells (such as monitoring wells) and to a lesser extent in slowly pumping wells. Areas with monitoring wells are typically waste sites, and various fluorescent compounds may be present in groundwater. In many cases the epikarstic zones laterally transport water along multiple flow routes to one or more surface streams; in such cases, multiple sampling stations will be needed on the streams to detect and localize dye discharge zones. All of these conditions require the use of good sampling and analysis strategies for detecting even small concentrations of the tracer dyes and for minimizing the chance of either false positive or false negative results. Typical approaches adequate for dye tracing from sinkholes to springs often lack the technical rigor needed for credible results in epikarstic zone groundwater tracing. In the following paragraphs we have identified some of the sampling and analysis approaches which we have found to be beneficial in groundwater tracing in epikarstic zones.

In most cases the most suitable dyes will be those which can be adsorbed onto activated carbon samplers. The dyes we most commonly use are fluorescein, eosine, and rhodamine WT. With careful selection of dye introduction points and the quantity of each dye used all three dyes can often be used concurrently at a site. Fluorescein is the dye typically selected for the most difficult or most critical trace. Rhodamine WT is the dye typically selected for the trace which is likely to be the easiest of the series; in some situations this dye will not function as an adequate groundwater tracing agent. Fluorescein and eosine can cause some fluorescence interference with each other; this is considered in selecting which dyes are introduced at which locations.

There are no equations which credibly determine the quantity of dye needed for tracing in epikarstic zones. Professional experience is essential; some generalizations may be useful. The thicker the epikarstic zone, the more dye will be needed. More dye is needed for tracing in perennially saturated epikarstic zones than in seasonally saturated epikarstic zones; rapid draining epikarst requires the least dye. Epikarstic zones where voids are abundant and are nearly filled with fine textured sediments require more dye than epikarstic zones where voids are less common or where the voids are less filled with sediments. Less dye is needed when EDIPs are used than when trenches that do not bottom in the epikarstic zone are used.

We place primary sampling reliance on activated carbon samplers which are typically collected, and new samplers placed, on a weekly schedule. This is particularly important at sites where other compounds are present which may adsorb onto the activated carbon. Grab samples of water should be collected each time a sampling location is visited; if dyes are detected in an activated carbon sampler, the water sample can be analyzed to determine dye concentration at a particular point in time. Furthermore, the presence of both activated carbon and water samples provides a verification of the presence of the tracer dye since the wavelength of a emission fluorescence peak for a tracer dye is a function of the dye and its matrix.

A good quantitative characterization of background fluorescence is needed prior to the final selection of dye types and quantities for a groundwater tracing study. Prior to the introduction of any tracer dyes we routinely conduct about three rounds of sampling at most (and preferably all) of the locations where sampling is planned after dye introduction. Emission fluorescence peaks in or near the acceptable wavelength range of one or more of the tracer dyes are sometimes encountered during background sampling. All emission fluorescence peaks in or near the acceptable wavelength range for a particular dye are quantified as if they were that dye. Acceptable wavelength ranges are calculated from field-derived data, and are specific to the analytical instrument used, the dye, and the dye matrix. Criteria for a positive dye recovery at a sampling station include a provision that, after dye introduction, at least one sample must have a dye concentration at least 10 times greater than the maximum concentration found in background samples from that location. This criterion has proven very useful at waste sites.

Sampling for tracer dyes in monitoring wells can be conducted effectively by suspending an activated carbon sampler in the middle of the screened interval or, in the case of open-hole wells, in the middle of the saturated zone. Multiple samplers can be placed in wells with multiple screens or very long open-hole segments. A useful approach for placing the sampler is to attach it to the top of a dedicated bailer and lower that into the well. Disposable bailers are adequate for this purpose; the bailers also facilitate the collection of water samples. No pumping or purging of the monitoring wells is required.

The amount of activated carbon used in a sampler should be standardized, and should be no larger than the amount needed for laboratory analysis. Use of only part of the activated carbon placed in a monitoring well is, in our view, an undesirable approach for a well. When the total amount of dye in a well is small and water circulation in the well is minimal, the more charcoal used, the less dye is adsorbed on each unit weight of the charcoal. Furthermore, the recovery percentage of tracer dyes during elution increases as the dye concentration on the activated carbon increases.

The dye analysis approach used should be standardized by the laboratory doing the work. Among many factors, there should be standardization as to the amount of activated carbon used for analysis, the quantity and composition of the eluting solution used, and the duration of the elution period. There are many different solutions used to elute tracer dyes from activated carbon; most of them are quite adequate for at least some applications. Various laboratory studies have been conducted to assess the performance of different eluting solutions, but the relevance of this work to actual field conditions is limited. In reality, there are many suitable solutions. Suitable solutions will typically elute multiple dyes from a single sample, will yield good recoveries of all dyes present, will yield consistent results, and will minimize the magnitude of fluorescence peaks associated with background compounds. Some solutions may damage delicate laboratory equipment and for this reason are undesirable.

APPENDIX B

Resume of Thomas Aley

PERSONAL DATA

Born September 8, 1938 in Steubenville, Ohio. U.S. Citizen. Married, two adult children.

EDUCATION

University of California, Berkeley. B.S. in Forestry (1960).

University of California, Berkeley. M.S. in Forestry with emphasis in forest influences and wildland hydrology. (1962).

University of California, Berkeley. Department of Geography (1962-1963); emphasis in hydrology and geology.

University of Arizona, Tucson. Department of Watershed Management (1963-1964); emphasis in wildland hydrology.

Southern Illinois University, Carbondale. Department of Geography (1972-1973).
Emphasis in hydrology and geology.

PROFESSIONAL CERTIFICATION & REGISTRATION

Professional Hydrogeologist, Certificate Number 179, American Institute of Hydrology, Board of Registration. Granted 1983.

Certified Forester, Society of American Foresters. Granted 1996.

Professional Geologist, State of Arkansas Registration Number 1646. Issued 1991.

Professional Geologist, State of Kentucky Registration Number 1541. Issued 1994.

Registered Geologist, State of Missouri Registration Number 0989. Issued 1998.

Professional Geologist, State of Alabama Registration Number 1089. Issued 2003.

PROFESSIONAL SOCIETY MEMBERSHIPS

American Institute of Hydrology
Association of Ground Water Scientists and Engineers
Society of American Foresters
Missouri Consulting Foresters Association
National Speleological Society

HONORS AND AWARDS

1960. Pack Prize in Forestry. University of California.
1961. Membership in Xi Sigma Pi, honorary forestry society.

1972. Award for outstanding performance, United States Forest Service.
1972. U.S. Forest Service nominee for the American Motors Conservation Award.
1973. Lester B. Dill Award for significant contributions to speleology. Mississippi Valley-Ozark Region of the National Speleological Society.
1977. Chairman's Conservation Award. Mississippi Valley-Ozark Region of the National Speleological Society.
1979. J Harlan Bretz Award for outstanding contributions to the study of speleology in the state of Missouri. Missouri Speleological Survey.
1981. Outstanding Service to Education Award. Phi Delta Kappa honorary educational fraternity for southwest Missouri.
1981. Fellow. National Speleological Society.
1988. In The Name of Science Award. Springfield, Missouri Public Schools. In recognition of outstanding service and dedication to science.
2012. Berry Commoner Science in Environmental Service Award. Missouri Coalition for the Environment.

EMPLOYMENT HISTORY

1973 to Present. Director and President, Ozark Underground Laboratory, Protem, Missouri. Conducts or directs consulting and contract studies in hydrogeology, cave and karst related issues, and natural resource management of karst regions.

1966 to 1973. Hydrologist, United States Forest Service. Winona, Missouri and Springfield, Missouri. Directed the Hurricane Creek Barometer Watershed study, which assessed the interactions of land use and ground water hydrology in a forested karst area. Directed Grey Hollow study. Conducted "trouble shooting work" in Missouri, Arkansas, Wisconsin, Utah, Illinois, and Indiana. Left government service as GS-12.

1964 to 1965. Chief Hydrologist, Toups Engineering, Inc., Santa Ana, California. Duties included basic data collection and analysis for plaintiffs in Santa Ana Basin adjudication and similar work for defendants in San Gabriel Basin adjudication; these were both ground water basin adjudication suits. Directed technical work on ground water basin management and artificial recharge.

1963 to 1964. Teaching Assistant, Department of Watershed Management, University of Arizona, Tucson. Aerial photogrammetry and photo interpretation.

1963. Researcher, grant from Office of Naval Research, U.S. Navy, through Department of Geography, University of California, Berkeley. Conducted field studies on the origin and hydrology of caves in Jamaica, Haiti, and the Dominican Republic. Responsible for all field work. Work resulted in 3 publications.

1960 to 1963. Teaching Assistant and Research Assistant, School of Forestry, University of California, Berkeley. Teaching in aerial photogrammetry, photo interpretation, and forest influences. Research assistant in the same fields.

SUMMARY OF EXPERIENCE

42 years of professional experience in ground water and surface water hydrology, pollution control investigations, and land management issues with particular emphasis on soluble rock landscapes. The following projects are representative examples.

1. Hydrologic studies for land management and spring protection with particular emphasis on soluble rock regions. Numerous studies of this type have been conducted for local, state, and federal agencies in Missouri, Arkansas, Alabama, Kentucky, Illinois, Tennessee, Alaska, and Wyoming.

2. Expert witness testimony on pollution potential of underground injection of hazardous wastes into deep-lying soluble rocks in Oklahoma.

3. Expert witness testimony in ground water and surface water hydrology in Missouri, Arkansas, Oklahoma, Kansas, California, Alabama, Maryland, and Indiana.

4. Expert witness testimony on riverbank stability problems in Missouri before U.S. Senate Committees at request of Senator John Danforth of Missouri.

5. Member of 6-member review panel on the adequacy of testing to determine radionuclide migration from a radioactive waste disposal site at the Idaho National Engineering Laboratory, Idaho. Served as the only hydrogeologist on the panel.

6. Member of 6-member expert hydrogeology panel on hydrological issues associated with the St. Louis Airport Radioactive Waste Site.

7. Chairman of a 4-member "blue ribbon" panel established by the U.S. Forest Service to assess the significance of cave and karst resources in southeastern Alaska. The panel also assessed the extent to which land management activities were adversely impacting the resources.

8. Hydrologic consultant to St. Charles County, Missouri on clean-up of radioactive wastes at Weldon Spring Site, a former Atomic Energy Commission processing facility. Advised on actions to protect county well field from radioactive contaminants dumped in an abandoned quarry.

9. Ground water tracing in soluble rock landscapes, and delineation of recharge areas for spring systems. Work conducted in Missouri, Arkansas, Oklahoma, Indiana, Illinois, Kentucky, Tennessee, Alabama, Florida, Georgia, Texas, Maryland, Pennsylvania, New York, West Virginia, Arizona, Oregon, California, Wyoming, and Alaska. Foreign work in Canada, Barbados, Australia, Indonesia, and Peru. Ground water tracing in fractured rock landscapes in New Hampshire, Alabama, New Mexico, Minnesota, Idaho, Utah, and Washington. Ground water tracing in unconsolidated geologic units in New York, Massachusetts, Florida, North Carolina, South Dakota, Missouri, Arkansas, California, Oregon, Washington, Alaska, and British Columbia (Canada).

10. Hydrogeologic investigations of groundwater impacts from pipeline corridors. Missouri, Oklahoma, and Texas.

11. Ground water tracing investigations at mines in Virginia, West Virginia, Pennsylvania, New York, Missouri, Utah, Colorado, Montana, Irian Jaya Indonesia, and Peru.

12. Hydrologic investigations to determine sources of pollutants which caused fish kills at commercial fish farms in Missouri and Arkansas.

13. Hydrogeologic site investigations (and sometimes testimony) on municipal landfills with emphasis on site suitability and probability of ground water contamination. 21 sites in Arkansas, Missouri, Wisconsin, and Alabama.

14. Hazardous waste remediation investigations with emphasis on hydrogeology. Sites in Missouri, Arkansas, Kentucky, Pennsylvania, Maryland, Alabama, Tennessee, and California. Second opinion review of projects in Missouri, Kansas, and New York.

15. Impacts of food processing wastes on surface and ground water quality. Various projects in Arkansas and Missouri.

16. Hydrologic investigations of petroleum pollution of wells. Multiple sites in Missouri, Arkansas, and North Carolina.

17. Assessment of the hydrologic impacts of proposed geothermal energy development on the Santa Clara Indian Reservation, New Mexico.

18. Investigations on the extent and sources of sewage contamination in about 100 springs at Eureka Springs, Arkansas. Work involved the delineation of recharge areas for most of these springs and the identification of sewer line segments which had the greatest leakage problems.

19. Hydrogeologic hazard area mapping for proposed sewer line corridors in a sinkhole plain area south of Mammoth Cave, Kentucky. Work included hydrologic recommendations for minimizing exfiltration and monitoring strategies.

20. Hydrogeologic mapping of Greene County, Missouri to identify areas where sinkhole flooding and serious ground water contamination could result from land development.

21. Assessment of impacts of proposed highways on springs, caves, and endangered cave-dwelling species, Arkansas, Missouri, Indiana, Virginia, West Virginia, and Alaska. Similar work for airports in Missouri and Arkansas, and for coal-fired power plants in Missouri and Arkansas.

22. Identification and delineation of rare, threatened, and endangered animal species' habitats in caves and ground water systems. Studies in Arkansas, Missouri, Oklahoma, Tennessee, Alabama, and Illinois.

23. Health and safety assessment of Harrison's Crystal Cave, Barbados.

24. Health and safety assessment of natural radiation as encountered in caves open to the public in the United States. Development of industry standards under OSHA Alliance Agreement.

25. Various microclimate, hydrologic, biologic, interpretive, and management investigations of caves in Missouri, Arkansas, Tennessee, Kentucky, New Mexico, Arizona, California, Wyoming, Oregon, Alaska, British Columbia, New Zealand, and Australia.

26. Evaluation of 19 sites for designation as National Natural Landmarks; sites are in Indiana, Missouri, Arkansas, Iowa, Ohio, and New Mexico.

27. Assessment of hydrologic impacts of rock quarries. Multiple sites in Missouri, Arkansas, Maryland, Illinois, Alabama, and Alaska.

28. Assessment of the impacts of deep mining on regional hydrology. Missouri.

29. Preparation of sole-source aquifer designation petition. Missouri.

30. Delineation of wellhead protection zones for public ground water supplies in Arkansas, Missouri, Alabama, South Dakota, New Hampshire, Maryland, and Florida.

31. Feasibility study for creation of a national-scale American Cave and Karst Museum.

32. Instructor in numerous professional short-courses. These have included:

1) over 20 four-day courses in karst hydrogeology and groundwater monitoring sponsored by the Association of Ground Water Scientists and Engineers and by Environmental Education Enterprises;

2) two courses on groundwater site investigation techniques for health department professionals in Washington State; and

3) courses on land management in karst terrains for resource managers in West Virginia, Indiana, Kentucky, Tennessee, Missouri, Arkansas, Utah, Idaho, Oregon, Washington, Alaska, and New Mexico.

PUBLICATIONS

1. _____. 1962. Analytical review of Gurnee, Russell; Richard Anderson; Albert C. Mueller; and Jose Limeras. 1961. Barton Hill Project; a study of the hydrology of limestone terrain. National Speleological Society Bulletin. Vol. 23, Part I. 30p. Review in Cave Notes, Vol. 4:4, pp. 32-33.

2. _____. 1963. Water balances for limestone terrain. *Cave Notes*, Vol. 5:3, pp. 17-22.

3. _____. 1963. Basic hydrographs for subsurface flow in limestone terrain: theory and application. *Cave Notes*, Vol. 5:4, pp. 26-30.

4. _____. 1964. Sea caves in the coastal karst of western Jamaica. *Cave Notes*, Vol. 6:1, pp. 1-3.

5. _____. 1964. Echinoliths--an important solution feature in the stream caves of Jamaica. *Cave Notes*, Vol. 6:1, pp. 3-5.

6. _____. 1964. Origin and hydrology of caves in the White Limestone of north central Jamaica. Dept. of Geography, Univ. of Calif., Berkeley. 29p.

7. _____. 1965. Corrasional cave passage enlargement. *Cave Notes*, Vol. 7:1, pp. 2-4.

8. _____. 1965. Analytical review of Brown, R.F. and T.W. Lambert. 1963. Reconnaissance of ground-water resources in the Mississippian Plateau region of Kentucky. U.S. Geol. Surv. Water Supply Paper 1603. 58p. Review in Cave Notes, Vol. 7:2, pp. 9-13.

9. Crooke, Howard W., John M. Toups, and _____. 1965. Ground water recharge means "progress insurance" in Orange County, California. *Water and Sewage Works*, Vol. 112:7, pp. 257-261.

10. _____. 1967. Analytical review of Sweeting, M. M.; G. E. Groom; V. H. Williams; C. D. Pigott; D. Ingle Smith; and G. T. Warwick. 1965. Denudation in limestone regions; a symposium. Geographical Journal, Vol. 131, Part 1, pp. 34-57. Review in *Caves and Karst*, Vol. 9:1, pp. 5-6.

11. _____. 1967. Water balance study of Greer Springs, Missouri. *Caves and Karst*, Vol. 9:2, pp. 12-15.

12. _____. 1967. Analytical review of White, William B. and Victor A. Schmidt. 1966. Hydrology of a karst area in east-central West Virginia. *Water Resources Research*, Vol. 2:3, pp. 549-560. Review in Caves and Karst, Vol. 9:5, pp. 44-46.

13. _____. 1968. Hydrology of a karst watershed in the Missouri Ozarks. *Caves and Karst*, Vol. 10:6, pp. 49-55.

14. _____. 1969. Out of sight, out of mind. *Missouri Mineral Industry News*, Vol. 9:12, pp. 163-166.

15. _____. 1970. Temperature fluctuations at a small Ozark spring. *Caves and Karst*, Vol. 12:4, pp. 25-30.

16. _____. 1972. The sinkhole dump and the spring. *Missouri Conservationist*, Vol. 33:2, pp. 16-17.

17. _____. 1972. Groundwater contamination from sinkhole dumps. *Caves and Karst*, Vol. 14:3, pp. 17-23.

18. _____. 1972. Control of unwanted plant growth in electrically lighted caves. *Caves and Karst*, Vol. 14:5, pp. 33-35.

19. _____, James H. Williams, and James W. Massello. 1972. Groundwater contamination and sinkhole collapse induced by leaky impoundments in soluble rock terrain. *Engineering Geology Monographs*, Series 5. Missouri Geol. Survey and Water Resources. 32p.

20. _____. 1974. Groundwater problems in southwest Missouri and northwest Arkansas. *Missouri Speleology*, Vol. 14:2, pp. 1-13.

21. _____. 1975. Hydrology. IN: Gott, J. D. Soil survey of Mark Twain National Forest Area, Missouri. U.S. Dept. of Agric. Soil Survey Report, pp. 47-50.

22. _____. 1976. Caves, cows, and carrying capacity. *Proc. First National Cave Management Symposium,* pp. 70-71.

23. _____. 1976. Hydrology and surface management. *Proc. First National Cave Management Symposium*, pp. 44-45.

24. _____ and Mickey W. Fletcher. 1976. The water tracer's cookbook. *Missouri Speleology*, Vol. 16:6, pp. 1-32.

25. _____ and Doug Rhodes; Editors. 1977. *Proc. Second National Cave Management Symposium,* 106p.

26. _____. 1977. Comments on cave radiation. *Proc. Second National Cave Management Symposium,* pp. 75-76.

27. _____. 1977. Introductory comments on commercial and high value caves. *Proc. Second National Cave Management Symposium*, pp. 52-53.

28. _____. 1977. The Ozark Underground Laboratory. *Proc. Second National Cave Management Symposium,* pp. 94-98.

29. _____. 1977. A model for relating land use and groundwater quality in southern Missouri. IN Dilamarter, R. R. and S. C. Csallany, Editors. Hydrologic problems in karst regions. Western Kentucky Univ. Press, pp. 323-332.

30. _____. 1977. The Ozark Underground Laboratory. IN Sloane, Bruce; Editor. Cavers, caves, and caving. Rutgers Univ. Press, pp. 140-158.

31. _____. 1977. Springs and sewage. IN Sloane, Bruce; Editor. Cavers, caves, and caving. Rutgers Univ. Press, pp. 318-329.

32. _____. 1978. A predictive hydrologic model for evaluating the effects of land use and management on the quantity and quality of water from Ozark springs. *Missouri Speleology*, Vol. 18, 185p.

33. Harmon, R.S.; H.P. Schwarcz, and _____. 1978. Isotopic studies of speleothems from a cave in southern Missouri, U.S.A. IN: Zartman, Robert E. (Editor). Short Papers of the Fourth Intern'l. Conf. on Geochronology, Cosmochronology, and Isotope Geology. U.S. Geol. Surv. Open File Rept. 78-701.

34. _____ and Catherine Aley. 1979. Prevention of adverse impacts on endangered, threatened, and rare animal species in Benton and Washington Counties, Arkansas. Northwest Arkansas Regional Planning Commission, Springdale, 35p.

35. _____ and David I. Foster. 1979. Deep secrets and dark problems; studies of karst springs in the Ozark National Scenic Riverways. *Proc. Second Conference on Scientific Research in the National Parks,* Vol. 5, pp. 499-505. U.S. National Park Service.

36. _____. 1979. Do threatened and endangered species threaten or endanger commercial interests at show caves? *Down Under*, Vol. 14:2, pp. 24-26.

37. _____ and Kenneth C. Thomson. 1981. Hydrogeologic mapping of unincorporated Greene County, Missouri, to identify areas where sinkhole flooding and serious groundwater contamination could result from land development. Mo. Dept. of Natural Resources, map folio and project summary.

38. _____ and Danny Halterman. 1982. A conceptual characterization of the subsurface movement of toxic chemicals in soluble rock lands. *Proc. Fifth National Cave Management Symposium*, pp. 77-80.

39. _____. 1982. Hydrologic impacts of urbanization in the soluble rock lands of Greene County, Missouri. *Proc. Fifth National Cave Management Symposium*, pp. 61-69.

40. _____ and Cathy Aley. 1982. Interpretive training for show cave personnel. *Proc. Fifth National Cave Management Symposium*, pp. 91-92.

41. _____. 1984. Groundwater tracing in water pollution studies. *National Speleological Society Bulletin*, Vol. 46:2, pp. 17-20.

42. _____. 1985. Optical brightener sampling; a reconnaissance tool for detecting sewage in karst groundwater. *Hydrological Science and Technology Short Papers,* Vol. 1:1, pp. 45-48.

43. _____, Cathy Aley, and Russell Rhodes. 1986. Control of exotic plant growth in Carlsbad Caverns, New Mexico. *Proc. Sixth National Cave Management Symposium*, pp. 159-171.

44. _____ and Cathy Aley. 1986. Effects of land management on cave and water resources, Dry Medicine Lodge Creek Basin, Bighorn Mountains, Wyoming. *Proc. Sixth National Cave Management Symposium,* pp. 79-92.

45. Quinlan, J.F.and _____. 1987. Discussion of "A new approach to the disposal of solid waste on land" by R.C. Heath and J.H. Lehr. *Ground Water* Vol. 25:5, pp. 615-616.

46. _____. 1988. Complex radial flow of ground water in flat-lying residuum-mantled limestone in the Arkansas Ozarks. *Proc. Second Environmental Problems in Karst Terranes and Their Solutions Conference,* pp. 159-170. National Water Well Association.

47. _____. 1989. Assessing the areal extent of groundwater impacts in karst. *Third Annual Watershed Conf. Proc., Watershed Comm. of the Ozarks*, Springfield, MO, pp. 187-191.

48. _____. 1990. The karst environment and rural poverty. *Ozarks Watch* (Southwest Mo. State Univ.) Vol. 4:1, pp. 19-21. (Reprinted in "An anthology of Ozarks Watch", Ozarks Watch, Vol. 5:3, pp. 60-62).

49. _____ and Cathy Aley. 1991. Delineation and hazard area mapping of areas contributing water to significant caves. *Proc. Eighth National Cave Management Symposium*, pp. 116-122.

50. Stringer, Jeffrey W.; Bruce L. Slover; and _____. 1991. Speleoforestry; planning for an unseen resource. *Jour. of Forestry*, Vol. 89:12, pp. 20-21.

51. _____. 1992. The water below. *Ozark Watch* (Southwest Mo. State Univ.) Vol. 6:1 & 2, pp. 42-44.

52. _____, Catherine Aley, William R. Elliott, Peter W. Huntoon. 1993. Karst and cave resource significance assessment of the Ketchikan Area, Tongass National Forest, Alaska. Report by the Karst Resources Panel to the U.S. Forest Service. 79p. + appendixes.

53. _____. Some thoughts on environmental management as related to cave use. *Australian Cave and Karst Management Association Jour.* Vol. 17, pp. 4-10.

54. Field, Malcolm S.; Ronald G. Wilhelm; James F. Quinlan; and _____. 1995. An assessment of the potential adverse properties of fluorescent tracer dyes used for ground-water tracing. *Environmental Monitoring and Assessment*, Vol. 38:1, pp. 75-96.

55. Stone, Paul R. III; William C. Nelson; Dennis Bowser; _____; Thomas R. Tibbs; Rusi B. Charna; Edward M. Kellar; and Gerald J. Murphy. 1995. Defining contaminant flow pathways in a complex geologic terrain using dye tracer studies. *Proc. Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Remediation.* Nat'l Ground Water Assn. and Amer. Petroleum Institute, pp. 239-253.

56. _____. 1996. Procedures for tracing water with fluorescent dyes. Robert W. Seabloom, Editor. *Proceedings of 9th Northwest On-Site Wastewater Treatment Short Course and Equipment Exhibition.* Univ. Washington, Seattle, pp. 329-341.

57. Chilman, Kenneth; David Foster; and _____. 1996. River management at Ozark National Scenic Riverways. IN: Halvorson, William L. and Gary E. Davis, Editors. *Science and Ecosystem Management in the National Parks.* Univ. Ariz. Press, Tucson, pp. 295-317.

58. _____. 1997. Caves in crisis. Encyclopaedia Britannica Yearbook of Science and the Future, 1997, pp. 116-133.

59. _____ and Wilgus B. Creath. 1997. Chapter 5, Mining and hydrology. IN: Mineral Policy Center. Golden dreams, poisoned streams, pp. 125-142.

60. _____. 1997. Groundwater tracing in the epikarst. *The Engineering Geology and Hydrogeology of Karst Terranes; Proc. 6th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst.* A.A. Balkema, Rotterdam, pp. 207-211.

61. _____. 1997. Keynote Address: Dyes don't lie; practical karst hydrology. *Proc. Karst-water Environment Symposium.* Virginia Tech. Water Resources Research Center, pp. 1-8.

62. _____. 1997. Beyond the passage ends. IN: Taylor, Robert L. and Jonathan Beard (Editors). Guidebook for the National Speleological Society Annual Convention; Exploring Missouri caves, pp. 38-45.

63. _____. 1998. An editorial: The Illinois cave amphipod; a collection of classical problems. *Amer. Caves*, Vol. 11:1, pp. 8-11.

64. Stokes, T.R.; _____; and P. Griffiths. 1998. Dye tracing in forested karst terrain: a case study on Vancouver Island, British Columbia. *Post-Conference Proc. of the 8th. Intern'l. Assoc. of Geological Engineers*, Vancouver, B.C.

65. Mott, David N.; Mark R. Hudson; and _____. 1998. Water resources studies, geologic mapping, and dye tracing employed to develop a model of interbasin recharge, Buffalo National River, Arkansas. *Friends of Karst, Intern'l. Global Correlation Program Abstracts.* Western Kentucky University, Bowling Green, p. 26.

66. Hauwert, Nico M.; David A. Johns; and _____. 1998. Preliminary report on groundwater tracing studies within the Barton Creek and Williamson Creek watersheds, Barton Springs / Edwards Aquifer. Barton Springs / Edwards Aquifer Conservation District and City of Austin Watershed Protection Department. 55p.

67. George, Scott; _____; and Arthur Lange. 1999. Karst system characterization utilizing surface geophysical, downhole geophysical and dye tracing techniques. *Proc. 7th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst*. A.A. Balkema, Rotterdam, pp. 225-242.

68. Mott, David N; Mark R. Hudson; and _____. 1999. Nutrient loads traced to interbasin groundwater transport at Buffalo National River, Arkansas. *On the Frontiers of Conservation; Proc. of 10th Conference on Research and Resource Management in Parks and on Public Lands*, pp. 114-121.

69. _____. 1999. Modern dye-tracing data as fundamental input for karst modeling. IN: Palmer, Arthur N.; Margaret V. Palmer; and Ira D. Sasowsky (Editors). *Karst Modeling; Proc. of Karst Modeling Symposium*. Karst Waters Institute Special Publication 5. p. 228.

70. _____. 1999. The Ozark Underground Laboratory's groundwater tracing handbook. Ozark Underground Laboratory, Protem, MO. 35p. Revised 2002.

71. _____. 1999. Karst hydrology; the dye is cast. Keynote Address, *Proc. 13th Australasian Conference on Cave and Karst Management*, Mt Gambier, South Australia. Pp. 17-23.

72. Call, G.K.; ______; D.L. Campbell; and J. Farr. 1999. Use of dye tracing and recharge area delineation in cave protection and conservation on private land. Proc. 1997 National Cave Management Symposium, pp. 23-27.

73. _____. 2000. Water and land-use problems in areas of conduit aquifers. IN: Klimchouk, Alexander; Derek C. Ford; Arthur N. Palmer; and Wolfgang Dreybrodt (Editors). Speleogenesis; evolution of karst aquifers. National Speleological Society, Huntsville, AL. Pp. 481-484.

74. _____. 2000. Ubiquitous environmental contaminants: radon and radon daughters. Chapter 15, Section 15.3 IN: Lehr, Jay (Editor). Handbook of environmental science, health, and technology. McGraw-Hill. Pp. 15.20 to 15.29.

75. _____. 2000. Sensitive environmental systems: karst systems. Chapter 19, Section 19.1. IN: Lehr, Jay (Editor). Handbook of environmental science, health, and technology. McGraw-Hill. Pp. 19.1 to 19.10.

76. David N. Mott; Mark R. Hudson; and _____. 2000. Hydrogeologic investigations reveal interbasin recharge contributes significantly to detrimental nutrient loads at Buffalo National River, Arkansas. *Environmental Hydrology; Proc. of the Arkansas Water Resources Center Annual Conference*. Arkansas Water Resources Center Publ. MSC-284, pp. 13-20.

77. _____. 2000. Karst groundwater. *Missouri Conservationist*, Vol. 61:3, pp. 8-11.

78. _____. 2001. Discussion of "A conceptual model for DNAPL transport in karst ground water basins" by Caroline M. Loop and William B. White. *Ground Water*, Vol. 39:4, pp. 483-484.

79. ______. 2001. Fantastic Caverns Spring. IN: Bullard, Loring; Kenneth C. Thomson; and James E. Vandike. Missouri Dept. of Natural Resources, Mo. Water Resources Report No. 68, pp. 74-79.

80. David Bednar and ______. 2001. Groundwater dye tracing: an effective tool to use during the highway development process to avoid or minimize impacts to karst groundwater resources. IN: Barry F. Beck and J. Gayle Herring, Editors. Geotechnical and environmental applications of karst geology and hydrogeology. A.A. Balkema Publishers, pp. 201-207.

81. Hauwert, Nico M.; David A. Johns; James W. Sansom; and _______. 2002. Groundwater tracing of the Barton Springs Edwards Aquifer, Travis and Hays Counties, Texas. *Gulf Coast Association of Geological Societies Transactions*, Vol. 52, pp. 377-384.

82. ______ and David Ashley. 2003. Saving the Tumbling Creek Cavesnail. *Wings, Essays on Invertebrate Conservation*, Spring 2003, pp. 18-23.

83. Neill, H; M. Gutierrez; and _______. 2003. Influences of agricultural practices on water quality of Tumbling Creek cave stream in Taney County, Missouri. *Environmental Geology, International Journal of Geosciences*. Springer-Verlag. Published online 8 October 2003.

84. Moss, Philip L. and ______. 2003. Mapping presumptive habitat for subterranean aquatic species of concern. 2003 National Cave and Karst Management Symp., pp. 7j0-73.

85. _____, 2003. Findings from some hydrologic investigations in the epikarst. Epikarst; Proceedings of the symposium held October 1 through 4, 2003, Shepherdstown, WV Karst Waters Institute Special Publication 9. Pp. 79-84.

86. _____. 2004. Forests on Karst. IN: John Gunn (Editor). Encyclopedia of Cave and Karst Science. Fitzroy Dearborn Publishers, New York and London, pp. 368-369.

87. _____. 2004. Tourist caves; algae and lampenflora. IN: John Gunn (Editor). Encyclopedia of Cave and Karst Science. Fitzroy Dearborn Publishers, New York and London, pp. 733-734.

88. Evans, David; Henri Letient; and _____. 2005 Aquifer vulnerability mapping in karstic terrain Antamina Mine, Peru. Proc. Annual Mtng. Society for Mining, Metallurgy, and Exploration. 13p.

89. Elliott, William R; Stephen T. Samoray; Sara E. Gardner; and ______2005. Tumbling Creek Cave: an ongoing conservation and restoration partnership. American Caves, Spring 2005. Pp. 8-13.

90. ______; Kimberly Castillon; and John Sagendorf. 2006. Strategy for managing alpha radiation in show-caves to protect caves, cave employees, and cave businesses. Proc. of the 2005 National Cave Management Symposium, Albany, NY. Pp. 62-71.

91. Elliott, William R. and ______. 2006. Karst conservation in the Ozarks: forty years at Tumbling Creek Cave. Proc. of the 2005 National Cave Management Symposium, Albany, NY. Pp. 204-214.

92. Elliott, William R.; ______; and Catherine L. Aley. 2008. Conserving an Ozark cave. Missouri Conservationist, Vol. 68:10, pp. 17-21

93. _____. 2008. Chapter 15. Tracer tests- dyes. IN: Weight, Willis D. Hydrogeology field manual. McGraw-Hill. Pp. 675-698.

94. Elliott, William R.; Kathy Echols; David C. Ashley; _____; Alan Leary; and Paul McKenzie. 2008. Waterborne contaminants in Tumbling Creek Cave, Missouri. Proc. of 2007 National Cave and Karst Management Symposium, St. Louis. Pp. 107-123.

95. Moss, Philip and _____. 2008. Dye tracing and recharge area delineation for varied land management purposes in the Southwest Illinois karst. Proc. of 2007 National Cave and Karst Management Symposium, St. Louis. Pp. 138-143.

96. _____; Cathy Aley; Philip Moss; and Eric Hertzler. 2008. Hydrogeological characteristics of delineated recharge areas for 40 biologically significant cave and spring systems in Missouri, Arkansas, Oklahoma, and Illinois. Proc. of 2007 National Cave and Karst Management Symposium, St. Louis. Pp. 154-167.

97. _______. 2010. Management strategies for responding to White-Nose Syndrome in bats. National Speleological Soc. News, Feb. 2010, Pp. 10-14.

98. Klingel, Eric J.; Shiflet, Jason E.; _______. 2010. Fluorescent dye tracing for defining chlorinated ethene plume remediation targets. Remediation Summer 2010, Pp 111-119, www.interscience.wiley.com.

S: Internet\Keep\Resumes\resume-ta1.doc. Updated 10/11/2012